NASA TN D-169

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197230
27P.

NASA TN D-169

TECHNICAL NOTE

D-169

SPECTROGRAPHIC TEMPERATURE MEASUREMENTS IN A CARBON-ARC-POWERED AIR JET

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON December 1959

(NASA-TN-D-169) SPECTROGRAPHIC TEMPERATURE MEASUREMENTS IN A CARBON-ARC-POWERED AIR JET (NASA) 27 p N89-70629

Unclas
00/35 0197230

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SUMMARY

Free-stream temperatures in a carbon-arc-powered air jet have been measured in the range $3,700^{\circ}$ K to $5,400^{\circ}$ K by using a spectrographic method derived by combining the work of J. A. Smit (Thesis, Univ. Utrecht, 1950) with that of Knauss and McCay (Phys. Rev., 1937). The combined method utilizes the band radiation of the cyanogen molecule and depends upon the rotational energies of this species. The theoretically calculated line intensities have been presented in such a way as to require a minimum amount of refinement and procedure in the measurement application. The apparatus for such a measurement is described, and some representative measurements made on the 700-kilowatt electric-arc-powered air jet of the Langley Research Center are given and discussed.

INTRODUCTION

The arc-powered air jet was developed at the Langley Research Center to provide a means of simulating the stagnation temperatures and heating rates associated with atmospheric reentry. The jet apparatus is shown in figures 1 and 2. Air is supplied to the arc chamber and is heated by a three-phase carbon arc striking between the three electrodes and the grounded carbon nozzle block. The air so heated then exhausts to the atmosphere through a contoured supersonic nozzle at a Mach number of approximately 2 and is highly luminous. A complete description of this apparatus and its operation is given in reference 1.

The measurement of the temperature of this gas cannot be accomplished by thermocouple or similar techniques, since the stagnation temperature of the jet is well above the melting temperature of any known solid material. Ordinary color or total-radiation pyrometric techniques are not applicable, since the gas radiation is not a continuous spectrum.

Several authors, however, have presented spectrographic methods of measuring the gas temperature in ordinary carbon arcs. A combination of two such methods of a particularly fundamental nature has been chosen as the basis for these measurements. (See refs. 2 and 3.) In this method, the distribution of energy among the rotational energy states of the cyanogen (CN) molecule is observed. For these measurements, the theoretical spectral line intensities have been presented in a way similar to that applied to the carbon monoxide band radiation by Knauss and McCay (ref. 2) which greatly simplifies the reduction of data in the temperature range of the jet.

Some representative measurements made in the 700-kilowatt electric-arc-powered air jet of the Langley Research Center indicate that the free-stream temperature varies between 4,000° K and 5,000° K depending on the power input to the arc.

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SYMBOLS

I	line intensity
h	Planck's constant
k	Boltzmann's constant
ν	wave number (reciprocal of wavelength)
A	transition probability
N	number density of particles
T	absolute temperature
g	statistical weight
Z	partition function
E	excitation energy
j	rotational quantum number

Subscripts:

l	line
b	band
s	system
el	electronic (energy state)

vib	vibrational (energy state)
rot	rotational (energy state)
t	total
0,1,2	numbering indices (first and second lines, and so forth)
P	P branch
R	R branch

Single-primed values indicate upper energy state, whereas double-primed values indicate lower energy state.

GENERAL COMMENTS

The problem of defining and measuring the temperature of a hot gas has been extensively treated by various authors. The definition of the temperature of such a gas is in itself complex, since, in addition to the kinetic energy of translation, there also exists energy in the rotational and vibrational excitation of molecules and the electronic excitation and ionization of atoms and molecules. This definition has been discussed at length by several authors, among these O. Preining (ref. 4) and J. A. Smit (ref. 5), and no attempt to be complete in this respect will be made except where necessary in connection with the temperature measurements reported.

The excitational modal temperature (that is, the temperature associated with a particular type of excitational energy, for example vibrational energy) is defined as that quantity which exists when the distribution of particle populations among the set of energy states associated with that mode can be described by the Boltzmann function. If, then, all the modal temperatures exist and are equal, thermodynamic equilibrium is said to exist.

It therefore seems necessary to determine the population distribution in each energy mode, the modal temperatures being determined separately, in order to gain a complete knowledge of the energy state of the gas. When thermodynamic equilibrium can be assumed, however, it is necessary to measure only one modal temperature in the system. In many cases, as in the ordinary carbon arc at atmospheric and higher pressures, published investigations (for example, refs. 5 and 6) have shown that thermodynamic equilibrium does exist. Under this circumstance, it is generally possible to select a method of temperature measurement on the basis of ease, reliability, and sensitivity.

Spectrographic methods of temperature measurement supply a means of measuring modal temperatures. In general, rotational, vibrational, electronic and ionization temperatures can be measured from either the relative or absolute intensities of spectral lines, and ionization and translational temperatures can be determined from the shapes of spectral lines.

Although the existence of thermodynamic equilibrium has not been definitely established in the carbon-arc-powered air jet exhausting to atmospheric pressure, it was thought that it could be assumed on the basis of considerations to be discussed in a later section entitled "Qualification of the Measurements."

Under this assumption, a basic temperature-measurement method was chosen which would be valid if equilibrium did exist and which had other advantages. It has been found convenient by various investigators (refs. 3, 5, 6, and 7) to use the radiation in the violet-band system of CN for the determination of carbon-arc temperatures. In particular, J. A. Smit (ref. 3) has found that the fine structure of the 0→1 vibrational band of the $^2\Sigma \rightarrow {}^2\Sigma$ electronic transition contains a group of lines whose relative intensities are sensitive to temperature and are easily measured.

This band has several features which make it convenient for use in temperature measurements. It is found to be strong in the spectrum of a wide variety of electrical discharges in air or nitrogen, as well as in some flames. A spectrum of the arc-powered air jet including this band is shown in figures 3(a) and 3(b), where figure 3(b) shows a magnification of the 4,216-angstrom to 4,197-angstrom region of figure 3(a). As can be seen in figure 3(a), the 0→1 band falls at the first of a band sequence and is hence not completely overlapped by other bands of this sequence. Because it falls at 4,216 angstroms in the violet region, any black-body continuum present in the gas is generally weak near this band.

The individual rotational lines upon which a measurement may be based are shown in figure 3(b). Here it can be seen that the individual lines are well resolved in the tail of this band. Each of these lines is actually a multiplet but the spacing is so small that this multiplet structure is unresolved. This is in itself convenient, since the total intensity of the multiplet is usually calculated, and considerable difficulty is frequently encountered in measuring the total intensity of resolved multiplets.

CYANOGEN BAND CALCULATIONS

The violet CN bands are considered to be nearly ideal examples of simple diatomic molecular radiation, and various properties of the molecule and its radiation have been treated extensively. (See ref. 8.) A complete description of the mechanisms in the molecule responsible for the form of the molecular bands of this type may be found in reference 8 or in reference 3. In particular, reference 8 gives the formulas necessary for calculating the wavelengths, or wave numbers, of any line of the CN bands. These formulas are derived from the quantum mechanics, and the constants needed for the calculations are obtained (as described in ref. 8) from spectral data.

The form of the bands is due to the magnitudes of each type of energy transition. (See ref. 8.) The whole band system corresponds to the same electronic energy transition, whereas each band is made up of lines all corresponding to the same vibrational transition. Each line is then distinguished by a particular rotational energy transition.

In the case of the CN molecule undergoing this particular electronic energy transition, the selection rules allow two rotational energy transitions from any one upper rotational energy state, these transitions corresponding to a change in the rotational quantum number by ± 1. This leads to the formation of two branches of the band, one corresponding to a change of 1, the other to -1; thus, two lines, one in each branch, have the same initial quantum number j'. One branch is called the P branch, the other the R branch. In figure 3(c), which is approximately a graph of the variation of intensity with wavelength for this band, the two branches have been indicated, as have the quantum numbers of 12 of the lines, 6 from each branch. It is these lines which are to be used in the temperature measurement. When the expressions for the intensity of these band lines are investigated, it can be seen that the form of the band makes the relative intensities of these lines particularly attractive for use in measuring temperatures.

The relationships necessary for the calculation of the relative intensity of the CN band lines involved in this temperature-measurement method may be extracted from reference 3 as follows: The intensity of any spectral line is given by

$$I = h\nu_l A_l N' \tag{1}$$

whereas the temperature dependence of N' with respect to N_t is given by the Boltzmann relation

$$N' = N_t g' \exp\left(\frac{-E}{kT}\right) \tag{2}$$

For a diatomic molecule it is convenient to consider

$$\frac{I}{N_t A_s} = h\nu_l \frac{A_l N'}{A_s N_t} \tag{3}$$

Expressions may then be derived for factors appearing in this equation. L567
For a line of the P branch

$$\frac{A_l}{A_s} = \frac{j_P' + 1}{2j_P' + 1}\left(\frac{\nu_l}{\nu_b}\right)^3 \frac{A_b}{A_s} \tag{4a}$$

whereas for the R branch

$$\frac{A_l}{A_s} = \frac{j_R'}{2j_R' + 1}\left(\frac{\nu_l}{\nu_b}\right)^3 \frac{A_b}{A_s} \tag{4b}$$

The Boltzmann relation assumes the form

$$\frac{N'}{N_t} = (2j' + 1)\frac{g_{el}'}{Z_t} \exp\left(-\frac{E_{el}' + E_{vib}' + E_{rot}'}{kT}\right) \tag{5}$$

By using these values, equation (3) becomes

$$\left.\begin{aligned} \frac{I}{N_t A_s} &= h\nu_l{}^4 \frac{j_R' A_b g_{el}'}{\nu_b{}^3 A_s Z_t} \exp\left(-\frac{E_{el}' + E_{vib}' + E_{rot}'}{kT}\right) \\ \frac{I}{N_t A_s} &= h\nu_l{}^4 \frac{\left(j_P' + 1\right) A_b g_{el}'}{\nu_b{}^3 A_s Z_t} \exp\left(-\frac{E_{el}' + E_{vib}' + E_{rot}'}{kT}\right) \end{aligned}\right\} \tag{6}$$

Finally, calculating the relative intensities of the two lines for the same band (that is, same molecule, same electronic transitions, and same vibrational transitions), where

$$N_{t_1} = N_{t_2} \qquad A_{s_1} = A_{s_2}$$

$$\nu_{b_1} = \nu_{b_2} \qquad A_{b_1} = A_{b_2}$$

$$g'_{el_1} = g'_{el_2} \qquad Z_{t_1} = Z_{t_2}$$

$$E'_{el_1} = E'_{el_2} \qquad E'_{vib_1} = E'_{vib_2}$$

yields

$$\left.\begin{aligned}
\frac{I_{R_1}}{I_{R_2}} &= \frac{{\nu_{l_1}}^4}{{\nu_{l_2}}^4} \frac{j'_{R_1}}{j'_{R_2}} \exp\left(-\frac{E'_{rot_1} - E'_{rot_2}}{kT}\right) \\
\frac{I_{P_1}}{I_{R_2}} &= \frac{{\nu_{l_1}}^4}{{\nu_{l_2}}^4} \frac{j'_{P_1} + 1}{j'_{R_2}} \exp\left(-\frac{E'_{rot_1} - E'_{rot_2}}{kT}\right) \\
\frac{I_{R_1}}{I_{P_2}} &= \frac{{\nu_{l_1}}^4}{{\nu_{l_2}}^4} \frac{j'_{R_1}}{j'_{P_2} + 1} \exp\left(-\frac{E'_{rot_1} - E'_{rot_2}}{kT}\right) \\
\frac{I_{P_1}}{I_{P_2}} &= \frac{{\nu_{l_1}}^4}{{\nu_{l_2}}^4} \frac{j'_{P_1} + 1}{j'_{P_2} + 1} \exp\left(-\frac{E'_{rot_1} - E'_{rot_2}}{kT}\right)
\end{aligned}\right\} \qquad (7)$$

Note that in the band, shown in figure 3(b), several lines show separately (those marked with rotational quantum numbers) so that their intensities may be measured easily. Note then also that each of these lines is associated with the same electronic and vibrational energy transition. It can then be seen that the ratio of intensities of any two of these lines can be given by expression (7). Here the only factors entering into the calculation are the quantum numbers of the lines (the upper energy state numbers), the wave number of the lines, and the values of the upper energy states. The wave numbers of the lines can be measured and calculated very accurately (as done by Smit, ref. 3) and the energy states can be calculated from the quantum mechanics and a few basic constants which have been accurately measured.

It must be understood here that this development is strictly valid only for complete thermodynamic equilibrium and in the absence of self-absorption (that is, for an optically thin gas). The final expression, however, will yield a rotational modal temperature even in the absence of equilibrium.

The theoretical expressions for the line intensities must then be presented in such a manner as to allow a comparison to be made between these intensities and those derived from the spectrogram of the arc jet. This may be done according to reference 3. Using expression (7), a family of curves of the logarithm of relative line intensity plotted against the
reciprocal of the temperature is drawn, and all 12 intensities are com- L
pared simultaneously with those determined from the spectrogram of the hot 5
gas. In the case of the arc jet, however, where the temperature lies 6
between 3,700° K and 5,400° K, a much simpler method of presenting these 7
intensities, first used by Knauss and McCay (ref. 2), can be found. Knauss and McCay, working with the bands of CO at fairly low temperature (< 800° K), found that some of the properties of the envelopes of the branches of a band might be used to measure the temperature. In the case of the CN band to be used, only those lines marked with quantum numbers are easily resolved; thus only these lines can be considered separately for the temperature measurement (the lines farther toward the head of this band actually consist of two lines superimposed). In this quantum number set, one of the temperature criteria of Knauss and McCay is useful, namely, the intersection wave number of the two branch envelopes.

The method used to obtain a theoretical graph of intersection wave number plotted against temperature is outlined briefly. The intensities of five of the R lines and the six P lines are calculated relative to R_6 from equation (7). This is simply performed by using $j'_{R_2} = 6$; $j'_{R_1} = 7, 8, 9, 10,$ and 11; and $j'_{P_1} = 52, 53, 54, 55, 56,$ and 57. The wave numbers and excitation energies are obtained directly from reference 3. The intensities are calculated at 4,000° K, 4,500° K, and 5,000° K, and are plotted against wave number in figure 4. When the branch envelopes are drawn through these calculated intensities, it is clear that three intersection wave numbers are determined, one for each temperature.

It is interesting to note that three widely separated parallel envelopes emerge for the P branch, one for each temperature, whereas the three R branch envelopes are almost coincident. This condition means that the relative intensities of the members of one branch, in the small quantum number range considered here, do not change appreciably over this temperature range, whereas the relative intensity of one branch with respect to the other depends appreciably on the temperature. This behavior can be easily explained from equation (7). Here it is seen that the temperature sensitivity of the relative intensities is determined by the difference in the excitation energies of the rotational energy states, which in turn depend essentially on the difference in squares of the quantum numbers. (See ref. 3 or 8.) Thus the temperature sensitivity of one branch line to another is very small, the quantum numbers differing by a maximum of 5, whereas the quantum numbers in the two branches differ by about 50. The R branch exhibits nearly coincident lines, instead of a group of widely separated parallel lines, because of the use of R_6 as a reference. These three intersections can then be used to determine a graph of intersection wave number against temperature, as in figure 5. This curve forms the pyrometric curve, since all that need be determined from the spectrogram of the arc jet is the intersection wave number of these two branches.

APPARATUS AND TECHNIQUES

Apparatus

The experimental problem, then, is to obtain sufficient data on the line intensities to allow a determination of the intersection wave number of the two branches on this band. In order to obtain these data, the spectrum is first recorded by means of a spectrograph. In the present measurements, the spectrograph and the jet were in separate rooms, and a system of front-surface mirrors was used to focus a full-size real image of the jet on the spectrograph slit. (See fig. 6.)

The instrument used in these measurements is a 2.25-meter Ebert mount grating spectrograph. The grating is a 15,000 line per inch original ruling which, when used in the second order, gives a dispersion of about 4 angstroms per millimeter. The spectrogram is obtained on a 4 inch × 10 inch Kodak photographic plate (type 103-0). With this instrument an exposure of 6 seconds was required. Spectral lines appear as dense lines on this photographic plate. The transmission of the plate was measured and recorded by a microphotometer. This record has been reproduced in figure 3(c). Since the spectrograph is a stigmatic instrument, each spectral line on the plate is an exact image of the slit illumination. Thus, the temperature of different portions of the jet can be measured depending on which portions of the lines are photometered. (See fig. 6.)

The jet mechanism is described fully in reference 1 and is shown in figures 1 and 2. The jet issuing from the carbon nozzle is approximately 1/2 inch in diameter, and the Mach number is approximately 2. The jet gas is primarily air but contains approximately 7 percent carbon by weight. This carbon appears in the form of free cyanogen and diatomic carbon and an excess amount of carbon monoxide and carbon dioxide. The jet mechanism is about 4 feet high and the jet gas issues vertically.

The optical system was so arranged that the jet image appeared on the slit rotated 90° from its normal position. Thus the spectrograph slit intercepted a line on the image perpendicular to the direction of flow and about 1/4 inch from the nozzle.

Technique

The temperature measurement consists of determining the intersection wave number from the photometer record of the spectrogram of the
arc jet and using this wave number to determine the gas temperature from L
figure 5. This intersection wave number is singularly easy to obtain 5
from this record, since all that need be done is to sketch the branch 6
profiles through the tops of the lines of these branches as has been 7
done in figure 3(c). Here it will be noted that the entire set of lines for each branch influences the intersection wave number. Lines which appear to be much too strong for the neighboring branch lines (for example, R_7) are neglected entirely when drawing the envelopes, and, in general, the weaker lines are allowed to determine the intersection. This procedure is justified on the idea that lines like R_7 contain an appreciable amount of radiation from a foreign radiator such as iron and are therefore not indicative of the true rotational energy distribution. It is in fact true that iron is frequently found to appear in the jet spectrum, and that strong iron lines may be found to coincide with R_7 and R_{10}. There exists the possibility, however, that these strong lines may be due to perturbations within the CN molecule itself, as has been found by Herzberg (ref. 8). These perturbations would occur only under nonequilibrium conditions, and since there is evidence that the jet is in equilibrium, these strong lines are probably due to interference from iron.

Once the profiles have been determined, the quantum number of the line closest to this intersection is used in figure 5 to determine a temperature. Any attempt to interpolate the wave number between two lines is not justified by the accuracy with which the envelopes can be drawn.

It will be noted that, although the theoretical branch envelopes of figure 4 are virtually straight lines, the profiles drawn on the photometer record appear to be curved. Part of this effect is due to the fact that the photometer record abscissa is linear in wavelength but not in wave number. The most important effect, however, is that the plate transmission recorded by the photometer is not a linear function of the line intensity. It is for this reason that, in general, when measuring relative intensities from a photographic plate, a calibration curve of plate transmission plotted against intensity must be obtained empirically for each plate, and this curve is then used in measuring the intensities. It is thus an important feature of the intersection-wave-number method of interpreting the data that the need for quantitatively measuring line intensities is eliminated. Not only is the work considerably lessened but the inherent errors of plate calibration, which frequently constitute an appreciable fraction of the total errors in a measurement, are eliminated.

REPRESENTATIVE MEASUREMENTS

Jet Parameters

A series of tests were made in the Langley 700-kilowatt electric-arc-powered air jet to determine the dependence of the jet free-stream temperature on power input to the arc. The nozzle configuration and size were held constant as was the mass flow. The chamber pressure varied, of necessity, with the power input.

Temperature measurements were made during six tests, three at each of two jet conditions, that is, two power input levels. Table 1 shows these jet conditions along with the measured temperatures. The power to the arc was changed by varying the voltage between the electrodes and the grounded nozzle block. A servomechanism was used to hold this voltage constant during any one test.

Results of Temperature Measurements

The temperatures listed, one for each test, were obtained by averaging the temperatures measured at 10 points across the jet, as indicated in a previous section. Since the temperatures measured across the jet show no consistent temperature gradients, it is assumed that the differences observed are due to uncertainty in determining the intersection wave number and not to actual temperature variations. It is therefore felt that this averaging procedure yields a representative temperature for each exposure.

DISCUSSION

Qualification of the Measurements

The temperature measurements in the Langley 700-kilowatt electric-arc-powered air jet are, as is generally the case, subject to some qualifications. The most obvious of these is that thermodynamic equilibrium has been assumed. As was pointed out earlier, the existence of equilibrium is required if the measured temperature, based on the rotational energies, is to describe the general energy state of the gas. There is some evidence that thermodynamic equilibrium exists in the arc-powered air jet.

Several properties of the arc jet might lead to nonequilibrium in the jet gas. The first is the electric arc within the chamber. Although several investigations (for example, refs. 5 and 6) have established the existence of thermodynamic equilibrium in carbon arcs at atmospheric pressure and above, no such determination has been made in these arcs with a high net transfer of gas through the arcs. Secondly, when the gas heated by the arc passes out of the supersonic nozzle, it undergoes expansion and hence changes in temperature. Several theoretical considerations of relaxation times (for example, ref. 9) indicate that, for the moderate expansion ratio of this nozzle, and when the distance traveled by the gas between the arcs and the nozzle minimum and between the nozzle xit and the region of measurement are considered, thermodynamic equilibrium does exist. These investigations, however, do not specifically encompass the range of parameters of this jet and hence are not able to give a definite verification of the existence of equilibrium. Further theoretical or experimental investigations are necessary before a definite statement can be made.

Another primary qualification on these measured temperatures is that it is not known exactly where or when the measured temperature occurred. The spectrographic exposure time is 3 to 6 seconds; during this time the arc temperature and the shape of the temperature field change. High-speed motion pictures of the jet indicate that the cross-sectional temperature profile (as indicated by the luminosity alone) varies in a random manner at frequencies varying from 180 cycles per second up to several thousand cycles per second. In addition, the average enthalpy of the jet gas is known to increase with time; thus, it is suspected that the average temperature of the jet might change considerably during the exposure time.

The measured temperature corresponds to some sort of time average of the instantaneous jet temperature. However, since it is thought that the jet exhibits a rapidly changing average temperature and temperature profile and that the jet is optically thin, the spectrographic exposure probably yields a temperature strongly weighted toward the highest temperatures occurring in the jet. That this is true can be seen from the exponential dependence of the absolute intensity of the lines on temperature as shown in expression (1).

Lastly, it is not definitely known whether the jet stream is optically thin with respect to the CN bands. That it is optically thin is strongly suspected, because CN is present only in trace amounts, and the jet is transparent for ordinary photography. If the jet gas is not optically thin, and the cooler gases are absorbing radiation from hotter portions of the jet, then one would expect the measured temperature to be in error due to this absorption.

Discussion of Errors

It is difficult to estimate the errors in this measurement method. The primary source of error is that interfering radiation may be present in a sufficient number of the line intensities to cause an error in drawing the branch envelopes and hence in determining the intersection wave number. Since all the measurements made are apt to include this same radiation, the error will not be detected in repeated measurements. However, enough of the lines appear to fit a smooth curve to indicate that this error is less than $\pm 400^\circ$ K over the range measured. This $\pm 400^\circ$ K error corresponds to a shift of the intersection over $\pm 2\frac{1}{2}$ rotational lines. There exists in addition to this systematic error, an error due to the grain of the photographic plate. This error is easily estimated by repeated measurements and has been found to lead to a scatter over three rotational lines or over a temperature range of $\pm 200^\circ$ K. J. A. Smit has estimated the errors in the calculated intensities at less than that required to give a 1- to $1\frac{1}{2}$-percent error in temperatures; hence, this error is negligible with respect to the errors in the measured intensities.

It therefore appears that any one temperature measurement might be in error by 600° K, whereas repeated measurements will yield a temperature containing an error of less than 400° K. It is also seen that a temperature difference of as little as 200° K can be detected by repeated measurements.

An attempt may be made to correlate the measured parameters for the two jet conditions with the measured temperatures. A direct correlation is not easily achieved due to the lack of knowledge of the efficiency of the jet apparatus in heating the airstream. A correlation which may be made consists of calculating the efficiencies of the jet for the two power levels using the measured temperatures, and then comparing these two efficiencies with each other and with the efficiency derived from a rudimentary energy balance. In order to calculate the efficiency from the jet parameters and temperatures, the measured Mach number of 2.0 and the mass flow of 0.07 pound per second, along with a static pressure of 1.4 atmospheres, are assumed to be the same for both power levels.

The static enthalpies can then be found from the thermodynamic properties of air as given in reference 10. The static enthalpy is then added to the kinetic energy of the gas and compared with the total energy input per unit mass flow. This calculation yields an efficiency for the arc jet of 59.1 percent for condition I and 58.3 percent for condition II. Attempts at an energy balance for this jet indicate an efficiency between 40 and 60 percent. Although no great reliability is attached to these numbers, they do indicate that the measured temperatures are reasonable, although perhaps slightly high, for these jet conditions. It will be noted that the two measured efficiencies are essentially equal. If then a constant efficiency for the jet is expected, it would appear that the relation between the jet temperature for the two conditions has been accurately measured.

Advantages and Disadvantages of the Method

The advantages of this method of temperature measurement have been brought out in the body of the paper but are summarized here. Because it is based on the classical method of measuring arc temperatures originally presented by Ornstein and Brinkman (ref. 6), little doubt as to the validity of the theoretical development can be held. Furthermore, a sufficient number of separate intensities is involved to prevent a gross error in their interpretation. The method of correlating measured and calculated line intensities is such that photometric errors are eliminated and the labor involved in performing the measurement is held to a minimum.

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Several disadvantages of this method of temperature measurement may be mentioned. The primary disadvantage of the method is that the long exposure time required to obtain the well-resolved spectra necessary for the measurement leads to some uncertainty in the meaning of the measurement. It is likewise difficult to obtain dependencies on rapidly changing phenomena; for example, the time history of jet temperature or temperature near an eroding model placed in the jet stream. For this reason it would be advantageous to use a method, such as that proposed in reference 5, requiring only prism spectra, which might be obtained with exposure times on the order of 0.1 to 0.01 second.

Furthermore, in the case of the rapidly changing arc jet, direct photoelectric measurements cannot be applied to this method. Because of the rapid fluctuations, simultaneous measurements of all the intensities involved are necessary, and the mechanical problem of placing 12 or even 2 photoelectric sensors in the space of a few angstrom units is formidable. From this standpoint, it would seem desirable to use a method based on two intensities widely separated in wavelength, such as that suggested by Ahrens (ref. 11).

CONCLUDING REMARKS

The method of measuring arc jet temperatures presented in this paper utilizes the resolved band radiation of cyanogen molecules in the jet stream to determine the distribution of rotational energies and hence the rotational temperature of this species. It appears that the method presented is capable of yielding temperature values which are reasonable with respect to energy balance considerations, and which therefore provide a suitable parameter for the comparison of different jet conditions. The limitations, qualifications, and errors inherent in the method and its application to the measurement of arc jet temperatures are also enumerated and discussed.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., August 19, 1959.

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TABLE I.- MEASURED TEMPERATURES AND JET CONDITIONS

	Jet condition I	Jet condition II
Average power, kw	650	510
Average current, rms amp	1,620	1,820
Average potential, rms volts . . .	220	160
Average flow, lb/sec	0.07	0.07
	4,800	4,020
Temperature, °K	4,870	3,970
	4,800	4,000
Average temperature, °K	4,820	4,000

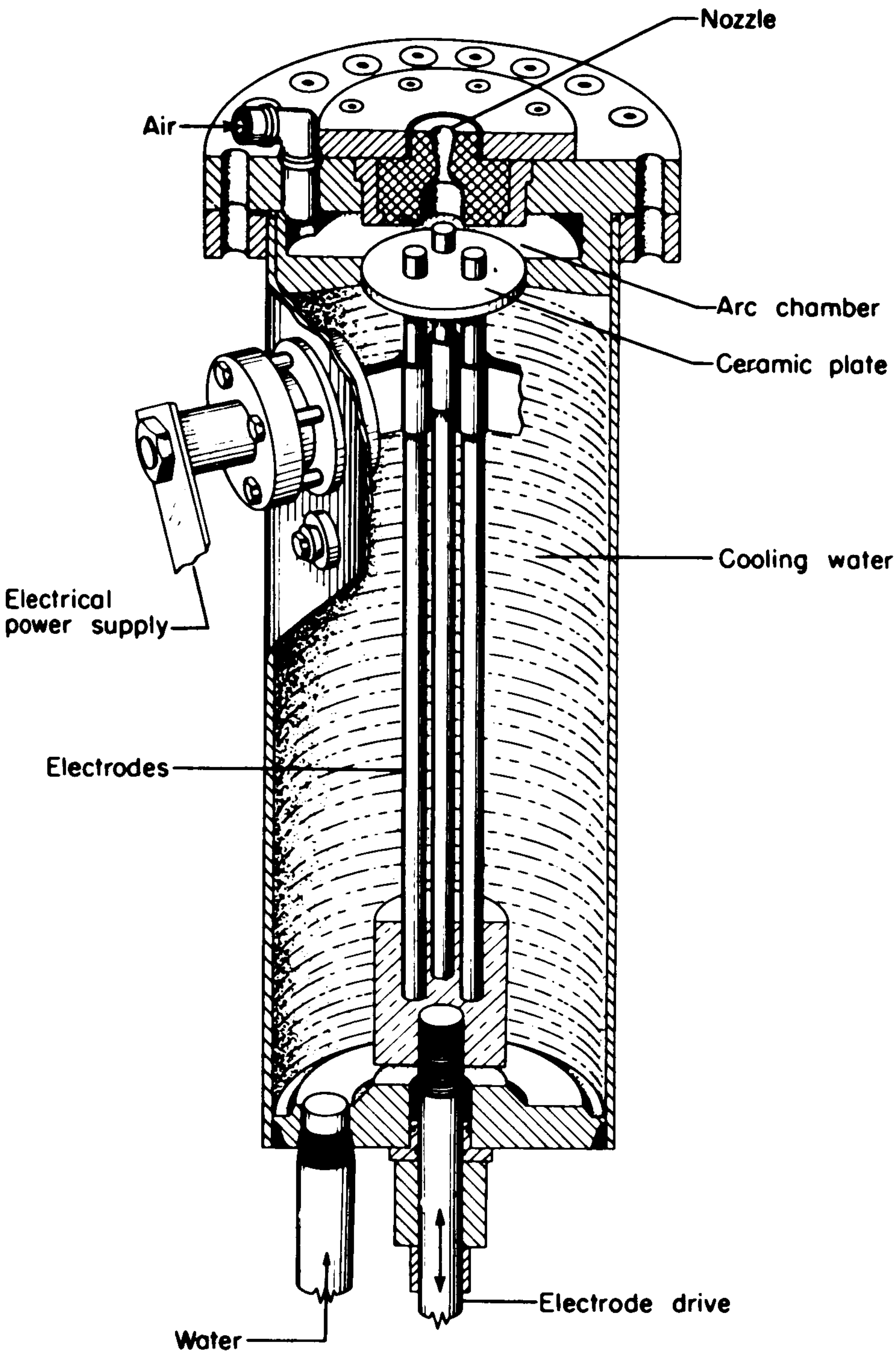


Figure 1.- 700 kw electric-arc-powered air jet.

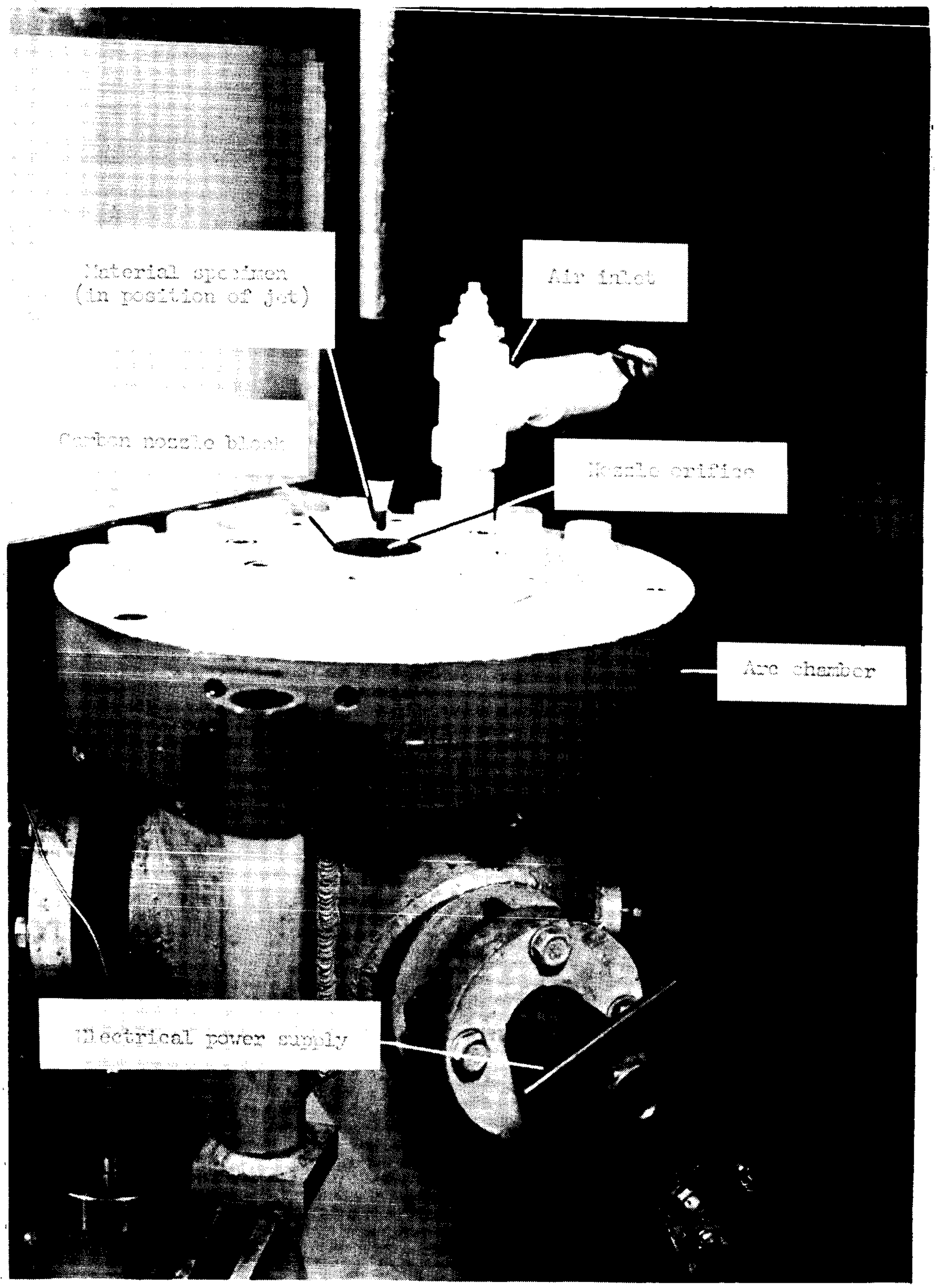
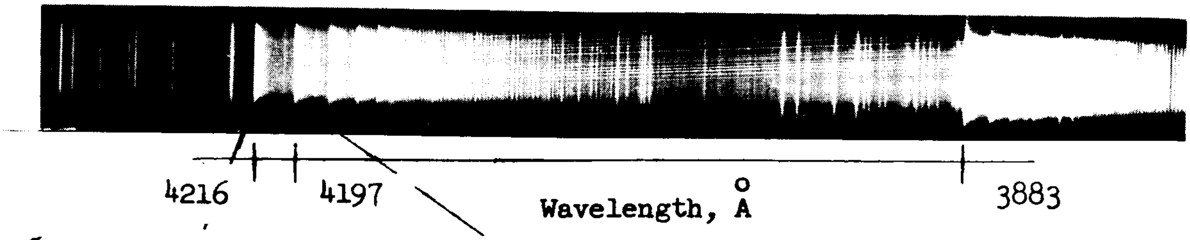
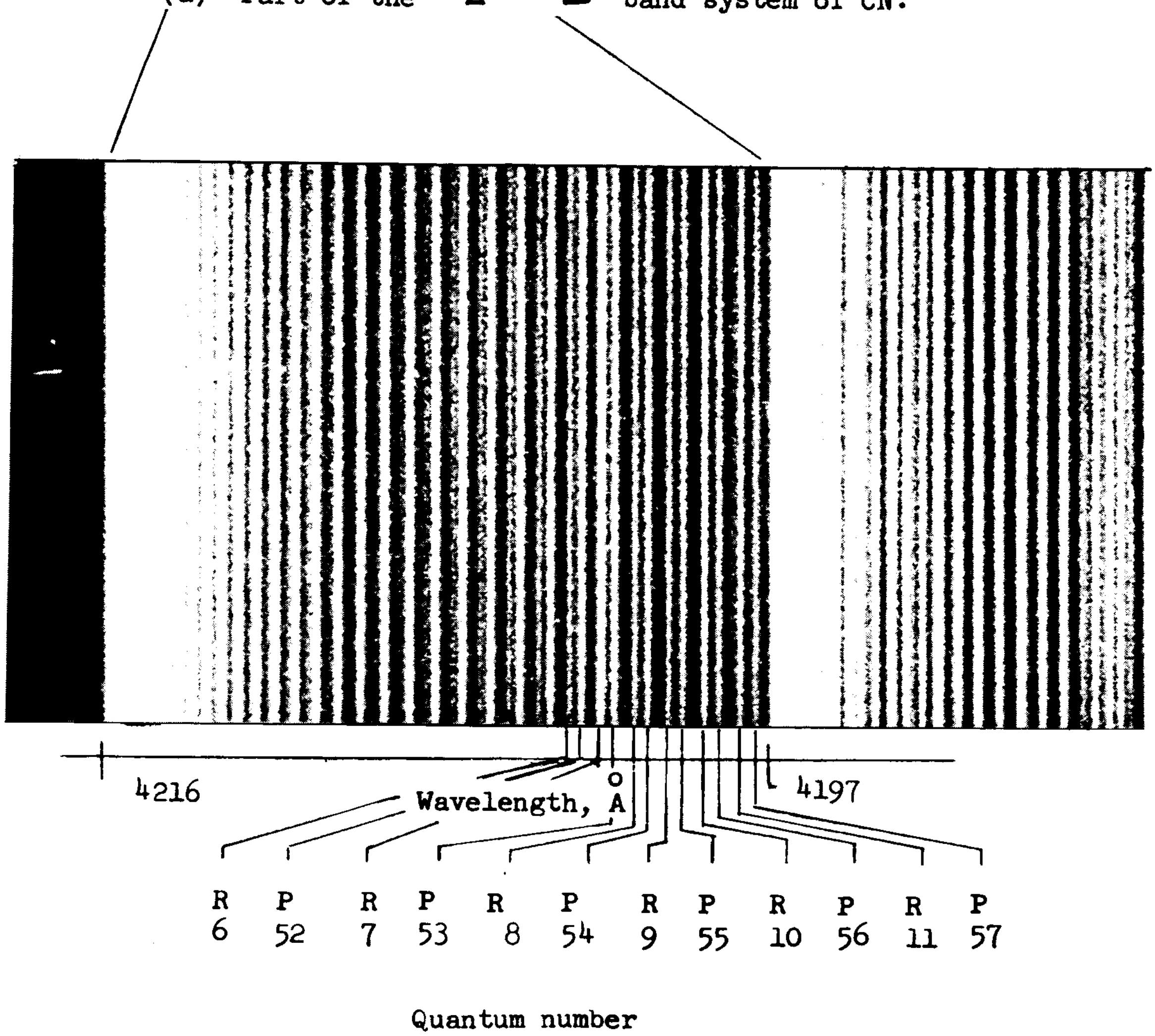


Figure 2.- Photograph of arc jet. L-57-5403.1



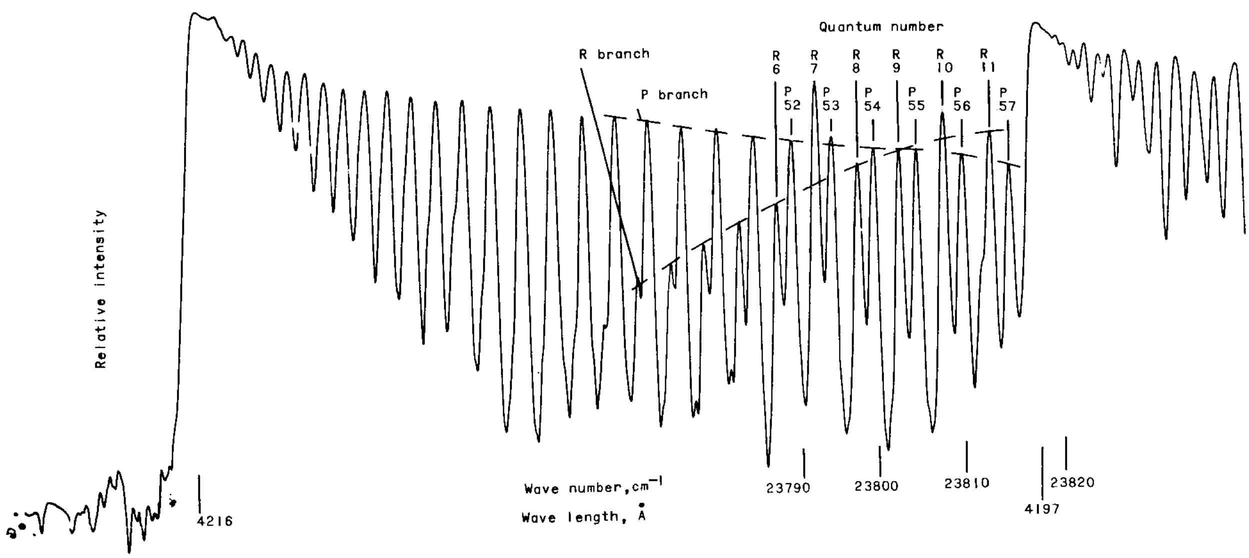
(a) Part of the $^2\Sigma \rightarrow {}^2\Sigma$ band system of CN.



(b) The 0→1 vibrational transition band of CN.

Figure 3.- CN spectrum from the arc jet.

L-567



(c) Microphotometer record of the 0→1 vibrational band of CN.

Figure 3.- Concluded.

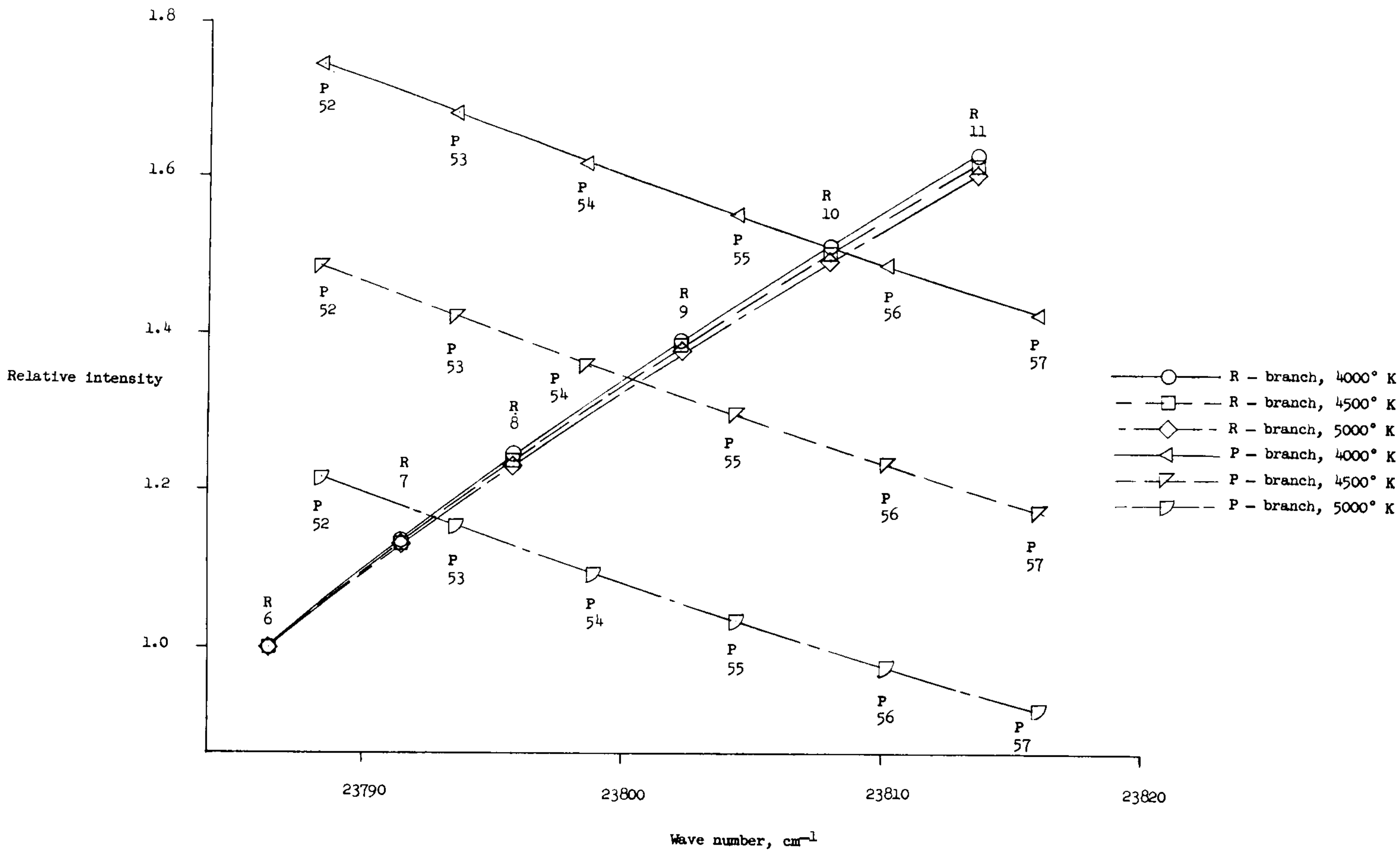


Figure 4.- Theoretical branch profiles for the 0→1 band of CN.

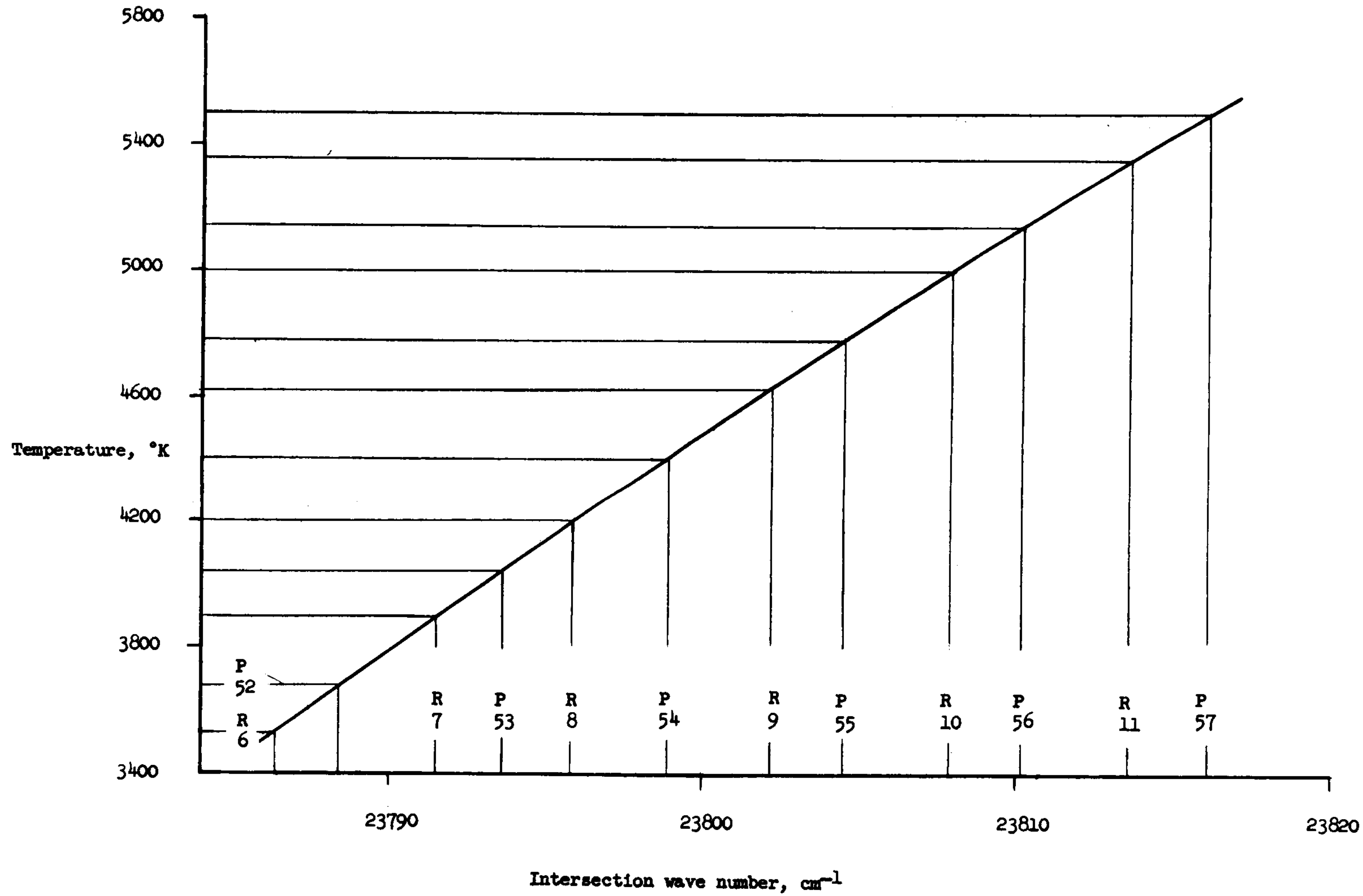


Figure 5.- Pyrometric curve for the 0→1 band of CN

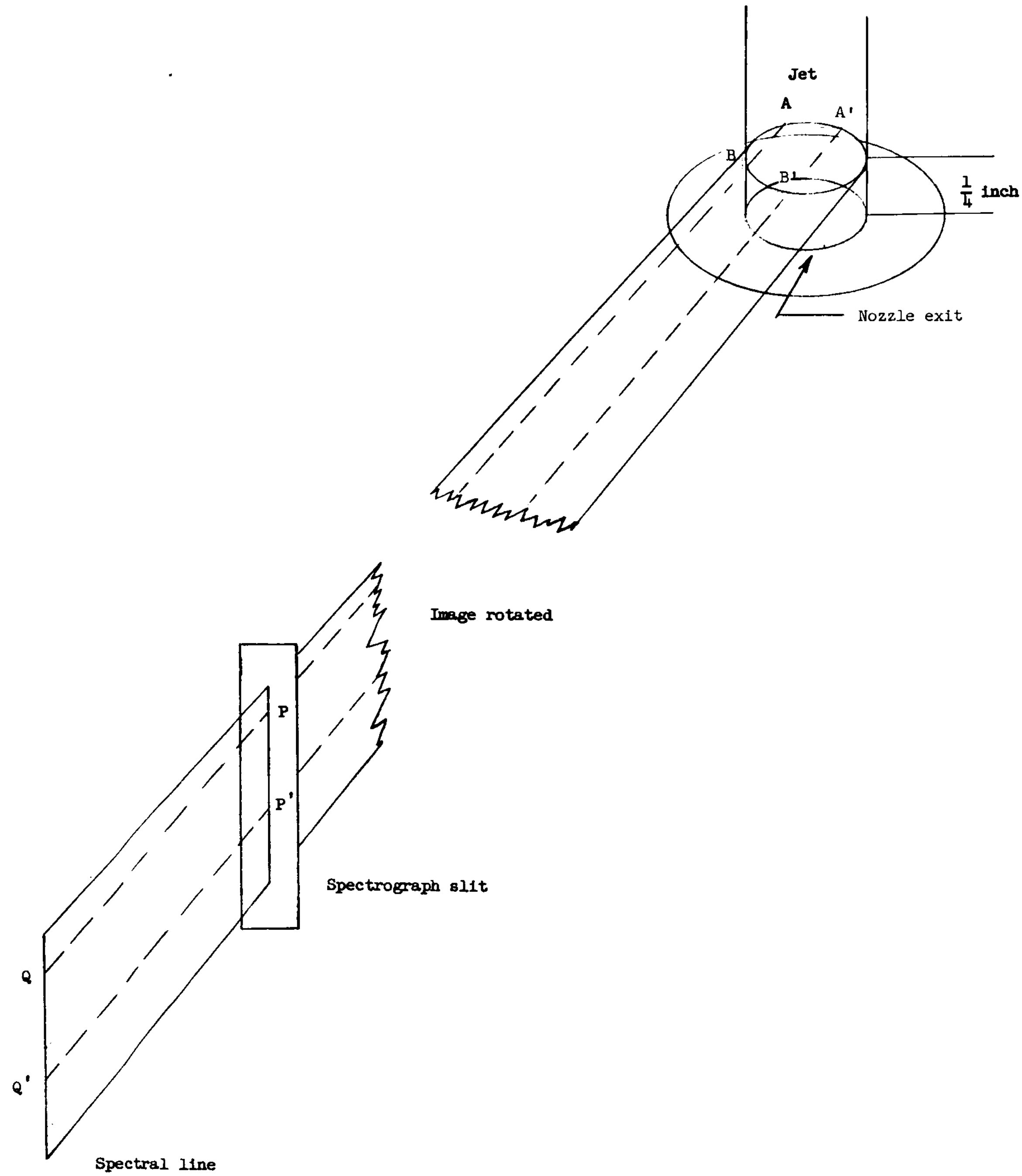


Figure 6.- Simplified diagram of optical point correspondence. Light originating in the jet along the line AB is focused on the slit at point P, and forms one point on the spectral line at Q.